SORPTION COOLING OF ASTROPHYSICS SCIENCE INSTRUMENTS

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ABSTRACT

This paper presents the current status of both continuous and periodic crpcl-alien sorption cryocooler development for astrophysics missions requiring refrigeration to 4 K and below. These coolers arc uniquely suited for cooling detectors in planned astrophysics missions such as the Exploration of Neighboring Planetary Systems Planet Finder Array. The cooler requirements imposed by these missions include ten year life, zero-vibration, zero EMI/EMC operation and the ability to scale designs to provide only a few milliwatts of refrigeration while consuming only a few watts of input power.

Spaceflight test results arc summarized for the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment. This experiment successfully validated flight cooler performance and provided characterization of all sorption cooler design parameters which might have shown sensitivity to microgravity effects. Ground test malls from a continuous 25 K cooler planned for usc in a long duration airborne balloon experiment are also presented. Finally, a NASA program to develop 30 K, 10 K and 4 K vibration-free coolers for astrophysics missions, which will start in FY 1997, is outlined.

Keywords: cryocoolers, sorption cryocoolers, telescopes, infrared telescopes

1. INTRODUCTION

The heritage provided by the many successful dewar cooled missions (e.g. ISO, IRAS, COBE, and the now underway WIRE and SIRTF) has enabled the serious consideration and development of a new generation of actively cooled space instrument design concepts. The interest in cryocoolers being shown by the designers of these missions is a result of the substantial maturation of cryocooling technologies, which has occurred over the past ten years, and of an increasing awareness within the scientific community of the potential benefits offered by these technologies. The utilization of long-life cryocoolers allows mission designers to refrigerate large format detector arrays during ten year missions. The volume and mass saved through the use of active coolers, in combination with passive radiators, enable mission designers to pack much larger telescope apertures into a given launch vehicle than would bc possible in a dewar cooled mission. Thus, many of the missions that launch after 2005 will incorporate cryocoolers.

Astrophysics missions now in the early design phase of development, which incorporate lon~-life, vibration-free cryocoolers include the Exploration of Neighboring Planetary Systems (ExNPS), the Next Generation Space Telescope (NGST) and Darwin. In addition to these precision pointing missions, moderate resolution missions such as FIRST and COBRAS/SAMBA arc incorporating low-vibration cryocoolers. This paper gives a discussion of the state-of-the-art in sorption cooler technology and how recent work in the field is being directed toward the goal of producing sorption coolers for future space based astrophysics missions.

2. FUTURE MISSION CRYOCOOLER REQUIREMENTS

Most of the mission concepts now under development will operate in thermally advantageous orbits for scientific and engineering reasons first pointed out by the EDISON team (Thronson, et al 1992). observing strategies and telescope/spacecraft configurations arc being, developed to fully exploit these orbits, which place all of the -300 K devices and structure together on a warm spacecraft bus oriented towards the san and earth. The cold telescope and science instruments are remotely located from the warm spacecraft bus and thermally isolated by several radiative surfaces, This enables optical structures to bc radiatively cooled to as low as 20 K without the use of coolers or dewars (Hawarden, et al 1992 and Wade, et al 1996).

While passive radiative cooling is very effective whca providing environmental shielding of extended structures and optics, it is often not very effective for absorbing actively generated loads (e.g. electronics, high bandwidth actuators, and detectors) at temperatures below 50 K. Typical requirements for astronomical telescopes which require active refrigeration include cooling al rmc or more of the following temperatures: approximately 25 K for high bandwidth actuators, InSb, and QWIP detectors; between 4 and 8 K for Si:As BIB arrays; at 4 K for Si:Sb BIB arrays, SIS heterodyne receivers, and for thermal sinking of magnetic, dilution, and Helium-3 coders used to cool bolometers to 0.1 K.

Several of the nmrc challenging requirements for active coolers are well illustrated by the ExNPS mission. The ExNPS program is tasked to detect, image, and characterize planets around other solar systems. The ExNPS Planet Finder Array (PFA) consists of four 1.5 m telescopes, passively cooled to 30 K, on a 75 m baseline which are operated as a nulling interferometer, a beam combiner that is also cooled to 30 K, and a detector that is cooled to 4 K. The PFA, along with its spacecraft bus and connecting structure, will be launched out to 5 AU using a Venus-Earth-Earth gravity assist trajectory on its nine year mission. The PFA must fit within an Atlas IIAS shroud (3.65 m diameter by 9.4 m long with 5.3 m of the length tapering to a 0.81 m diameter tip) and within rr lift capability of only 1824 kg. Due to the long duration of this mission, initially unfavorable thermal environment (especially during Venus flyby), and limited launch vehicle shroud volume and lift capability it is not feasible to use a dewar to support this mission.

The ExNPS PFA is designed to operate at 10 microns with a 20% bandwidth using destructive interference to 'remove' the light from the central star, which is 1,000,000 limes brighter than an carib-like planet would bc. Combining tbc high resolution of this away and the need to null the target solar system central star leads to a pointing requirement of appi oximately 10^{-6} arcseconds. Stirling and Pulse Tube coolers, 01- coolers using similar compressors, can not be used to actively cool the ExNPS PFA focal plane as the residual vibration perpendicular to the compressor axis is typically 0.2S N despite 9th harmonic vibration nulling electronics (Smedley, Johnson, and Ross 1995), To do better than this, three axis stabilization actuators would have to be incorporated into the compressor and expander, along with redundant actuators. Due to the high dimensional stability requirements (-- 10^{-10} m), stringent pointing requirements, and the difficulty of integrating this assembly into the beam combiner, usc of these coolers is not deemed feasible.

The solar array for this mission must be sized to enable observations at 5 AU when power is 25 times tougher to come by than at 1 AU. Therefore any cooler incorporated into the ExNPS design must have very low power requirements. To achieve this requirement, the cooler must be capable of taking full advantage of the favorable thermal environment enjoyed during observations and to scale down to a size commensurate with the ExNPS PFA mission detector cooling requirement of approximately 5 mW at 4 K. An additional stringent requirement is imposed by the desire to do spectroscopy on the detected neighboring planetary systems. In this mode, the final signal is measured in electrons pcr hour. Hence, essentially no cooler induced EMI/EMC is acceptable.

Only sorption coolers can meet the stringent combination of life, vibration, mass, volume, power, and EMI/EMC requirements posed by missions such as the ExNPS PFA.

3. STATUS OF SORPTION CRYOCOOLING TECHNOLOGY

3.1 Sorption Technology Summary

Several review papers have been published which describe the history and basic concepts behind the various kinds of sorption coolers (Wade 1993 and 1991).

The characteristics of sorption coolers which arc important to mission designers include:

1) The ability to locate all warm components directly on the preferred beat rejection surfaces to both minimize system mass, simplify the mechanical design, and to prevent thermal parasitics into the passively cooled regions of the telescope;
2) Minimized cryostat size to simplify integration into the science instrument beam combiner or focal plane assembly;
3) Dimensional stability on the order of the amplitude of lattice vibrations in a simple block of stainless steel;
4) Zero EMI/EMC effects on the science instruments;
5) Extremely imv power usage. This caa bc achieved through taking full advantage of the thermal environment to minimize environmental loads, intercept parasitic, and to precool the refrigerant, Combining the aggressive use of the thermal environment with the ability to linearly scale the size and thereby the input power to the cooler malts in extremely small system power requirements. Predicted rule-of-thumb performance ranges for coolers that provide less than 100 mW of cooling, reject their input power at approximately 300 K, and arc designed for flight arc:
   a) 300-400 W/W at 20 K
   b) 700-900 W/W at 9 K
   c) 3,000-5,000 W/W at 4K

   These estimates are based on a 60 K precooling temperature and designs incorporating fall flight and ground test safety margins. Therefore, a 5 mW, 4 K cooler can bc built for flight which requires less than 25 W of input power, Similarly, a 20 mW, 9 K requirement can be met with icss than 18 W of input power.

Recent advances have substantially improved the flight readiness level of sorption technology. The Brilliant Eyes Ten-Kelvin Sorption Cooler Experiment (BETSCE), (Bard, cl al 1993 anti 1997) which operated in orbit in May, 1996, examined all of the design characteristics which could bc affected by the microgravity environment. The resulting dataset provides flight validation for the design of future periodic and continuous sorption coolers,

A continuous operation 25 K cooler is being developed for tbc University of California at Santa Barbara (UCSB) long Duration Balloon (LDB) experiment (Wade and Levy 1997). This single-stage cooler was designed to robustly achieve stable performance while dramatically improving contamination tolerance.

3.2 Summary of BETSCE Flight Results and Accomplishments

BETSCE is a periodic operation cooler developed to achieve a cold cad temperature of less than 11 K in under 2 minutes from a starting temperature of 65 K. This experiment was flows on the space shuttle Endeavour during the May, 1996 STS-77 mission. As the first hydride sorption cooler flight experiment, it offered a unique opportunity to measure mitt ogravity effects.

'1 he in-flight performance of BETSCE has completely validated the use of hydride sorption coolers in space as no on-orbit degradation was found. The cooler successfully achieved a cold tip temperature of JO.4 K in icss than two minutes from an initial temperature of 70 K. The cooler provided i 00 mW of cooling for 10 minutes. This exceeded the BETSCE performance goals. la addition, a total of 8 quick cooldown cycles to liquid hydrogen temperatures were accomplished, achieving a minimum temperature of 18.4 K. A total of 18 compressor cycles were completed aad the ability to repeatably achieve the 10.1 MPa high pressures achieved in ground testing was successfi ally demonstrated.

The measured microgravity effects on characteristics of interest to all sorption cooler designers were:

1) $LaNi_{4.8}Sn_{0.2}$ and ZrNi hydride powder thermal conductivities were perhaps the most important properties to characterize well. The in-flight conductivities were determined, from the rate of absorption and the absorption pressure, to have been identical to those measured in a one-g environment.
2) Supercooling of the n-hexadecane phase change material in the Fast Absorber Sorbent Bed is important to most periodic operation cooler designs and to some continuous cooler designs. Nrr change in its expected 291 K melting temperature was observed.
3) The ability of the cryostat liquid reservoir to separate and retain both liquid aad solid hydrogen substantially affects cooler capacity and temperature stability. Again, no adverse microgravity effects were observed in the cryostat cold head.

In summary, the BETSCE flight data shows that no additional design margin is required to design a hydride sorption cooler for space missions. la addition, BETSCE clearly demonstrated the feasibility of successfully developing aad flying a sorption cryocooler in space.

3.3 2S K UCSB Long Duration Balloon Cooler

A continuous operation 25 K single-stage cryocooler is currently in final integration and test at JPL in support of a long duration balloon experiment to measure anisotropy in the Cosmic Microwave Background radiation. The 25 K LDB cook **is designed** to **provide** 480 mW of refrigeration with a temperature stability of better than 1 mK/s using a measured 220 W of input power. Precooling of the hydrogen and thermal shielding of the focal plane is provided by two Sunpower Stirling, cryocoolers. The final integration and performance testing of this cooler will be completed in fall 1996. Delivery and integration of this cooler into the UCSB dewar package will occur late in 1996. This UCSB LDB experiment is scheduled to fly over Antarctica for two weeks in December, 1997.

Since this cooler is the first hydride sorption cooler to be used to help gather science data, other than on the performance of the hydride cooler itself, it is also the first to be designed to support science instrument requirements. The use of this cooler in the LDB experiment has enabled the team at UCSB to realize substantial mission benefits by replacing their baselined 500 liter helium dewar. Flights of one to three months in duration, planned for future experiments, would be impossible without active cooling.

Because of the overriding concern to make the UCSB LDB cooler safe and rugged, it has been built at a level equivalent to flight engineering model hardware. Hence, all of the materials, fabrication and assembly techniques, and design and safely margins arc consistent with flight requirements.

The most significant innovations in this effort, when compared to previous sorption coolers, are in the materials selection and fabrication processes used to minimize contamination levels. This is especially important since the primary reliability concern for any J-T cooler is contamination. To achieve high reliability and to provide a better foundation for future flight missions, the cooler structure was entirely made of 316L VIM/VAR stainless steel. The Department of Energy's Ames Laboratory at lows State University provided $LaNi_{4.8}Sn_{0.2}$ material with a purity level over 10,000 times better than that used for fabrication of aay sorption cooler before this. Assembly of the cooler was conducted entirely in a purified and monitored Argon glovebox. Vacuum pump-out ports were provided to each volume within the refrigerator for contamination removal.

The cooler cryostat also has features incorporated which should enormously increase its tolerance to contamination. Porous plugs with a diameter of approximately 0.2 cm arc used for the actual expansion rather than the <0.002 cm diameter orifices more commonly chosen and arc expected to hc math more contamination tolerant. Additionally, a 0.01 micron filter is placed at the inlet of the J-T expansion element. The temperature of the refrigerant at this point will bc approximately 35 K. At 35 K even 1 ppm of air constituents, such as oxygen and nitrogen, will solidify aad can be filtered out of the refrigerant stream.

This demonstration that a hydride sorption refrigerator can bc fabricated in a lightweight, integrable package, and operate reliably despite a challenging environment will substantially advance the state-of-the art. The proof of detector compatibility, as demonstrated by the quality of the science data gathered, and verification of cooler reliability and ruggedness will significantly add to the heritage of sorption cooler development for future astrophysics missions.

3.4 Cooling to Ten Kelvin and Below

Continuous operation expanders for use below 10 K with hydrogen, originally proposed by Jones 1984 arc currently under active development. As hydrogen is a solid at this temperature with a vapor pressure of only 1,9 torr, a novel expander is used. Longsworth and Khatri (1996 aad 1995) recently described a successful laboratory test of such a device. Operation of this expander is initiated by using a standard J-T expansion technique to collect liquid hydrogen in a reservoir. If a pump (or sorbent bed) is then used to evacuate, the liquid reservoir which has a porous filter at its exit, a solid is formed. Stable continuous operation is then achieved with a temperature gradient in the refrigerant rc.set-i,oir. The result **is that** both liquid and solid hydrogen arc in the cold end. As the solid sublimates, the heat of fusion conducts back to the liquid reservoir to freeze replacement refrigerant and the heat of vaporization provides Useful refrigeration. Sach a 'glacier cooler' operated at 9.7 K.

4 K sorption coolers have been proposed for many years (Hartwig 1980). la the past however tbc cooling requirements

envisioned were usually between 0.1 and 1 W. The resulting power requirement quickly halted further development efforts. Reduced cooling requirements, coupled with the recent avai lability of hydride sorption coolers, have made use of these helium/charcoal coolers possible. A typical 4 K three-stage cooler concept is to use an activated charcoal, such as Saran carbon, cooled to 16 K by the first hydride stage as the sorbent material. The high pressure helium refrigerant is then precooled 109 K using the second hydride stage of the cooler.

4. SORPTION COOLER DEVELOPMENT 1'1 ,ANS

The primary thrust for the continued development of sorption cryocooler technology will be provided by a NASA Code X funded research and development program which starts in FY 1997. This effort will be focused on developing a series of vibralion-free cryocoolers at 30 K, 6 to 10 K and 4 K in support of precision pointing NASA astrophysics missions such as ExNPS and NGST. These coolers will be developed al an engineering model level and integrated into a sei ics of challenging science experiments in a manner similar to that followed in the 25 K LDB cooler effort.

The planned FY'97 effort will start with component development to determine the two major open issues remaining in sorption cooler development:

1) ('an a sorption compressor operate with stable performance for ten years of continuous operation?
2) Can the continuous operation, sub-10 K, hydrogen sublimation cryostat developed by Longsworth and Khatri provide stable long term cooling? And if so, at what minimum temperature?

The results of these efforts will then be fed into the development of a continuous sub-10 K cooler which is planned to start in FY 1998. This effort in tam will support the future development of a continuous operation 4 K cooler.

5, SUMMARY

Most of the sorption cryocooler development being actively pursued is focused on refrigerators which provide continuous cooling at temperatures below 30 K and at loads of well under 0.1 W. The successful flight of the BETSCE cooler has clearly demonstrated the suitability of sorption technology for spaceflight applications. The transition of these coolers from a development level primarily concerned with technology demonstration to a level primarily concerned with supporting aggressive science missions has been initiated with the development of the 25 K LDB cooler.

It seems reasonable that, with the planned development efforts, sorption coolers will reach maturation and, in doing so, enable several of the most ambitious and exciting scientific missions yet conceived.

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